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Early Trade-offs and Top-Level Design Drivers for Antarctic Greenhouses and Plant Production Facilities

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The development of plant production facilities for extreme environments presents challenges not typically faced by developers of greenhouses in more traditional environments. Antarctica represents one of the most inhospitable environments on Earth and presents unique challenges to facility developers with respect to environmental regulations, logistics, waste management, and energy use. The unique challenges associated with plant production in Antarctica heavily influence the selection of subsystem components and technologies as well as the operational paradigms used to operate the facilities. This paper details a wide array of the early design choices and trade-offs that have arisen in the development of Antarctic plant production facilities. Specific requirements and several guidelines stemming from the Antarctic Treaty's Protocol on Environment Protection and their influence on Antarctic plant production facilities are described. A review of guidelines for Antarctic greenhouses published by several national Antarctic operators is also described. The specific technology choices of several past and present Antarctic greenhouses are summarized, as are the general operational strategies, such as solid and nutrient solution waste handling. Specific lessons learned input was compiled directly from developers and operators of a number of these facilities. A discussion on the Antarctic climate, differences in Antarctic installation locations, internal versus external station plant growth facilities, preshipment testing programs, carbon dioxide enrichment and numerous other Antarctic facility design trade-offs are elaborated. It is hoped that this paper can serve as a useful checklist for future Antarctic plant production facility developers.

I. Introduction

The use of plants for food production began during the early days of Antarctic exploration, yet today it remains, at best, a small-scale ancillary activity of Antarctic stations. With only a few noteworthy exceptions, most projects have been largely expeditioner driven and hobby-like in nature and scale, being constructed with little pre-design work or planning. Advancing technology and greater emphasis on the provision of fresh produce, especially as a contributor to

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crew psychological well-being, has impelled the development of new projects and provided the opportunity for long-term projects that follow a more traditional and detailed engineering design process. Developing plant production systems for Antarctic deployment presents unique challenges. Several of the design challenges will be obvious from the outset, while others may not be so clear or intuitive. To aid developers in understanding top-level design choices and the pros and cons of each, this paper analyzes the technologies, operational strategies and lessons learned from numerous past and present Antarctic plant production facilities. As recently described, there have been more than 46 distinct plant production facilities that have operated at one time or another in Antarctica [1]. In addition to reviewing the published literature related to these projects, this paper presents information collected from direct communication with a number of the designers, operators and national contact points who have worked on these programs. Further lessons were compiled based on the authors' specific work on the EDEN ISS project, which will deploy a mobile greenhouse module at the German Neumayer III Antarctic station [2]. This experience, including the inevitable pitfalls, has highlighted the value that a reference document describing Antarctic plant production design challenges would provide to future designers. This resource is useful, both in terms of avoiding repetition of non-optimal design choices, but also to present as many lessons learned from past designers, including the unique factors influencing designs, as possible. Numerous influencing factors related to the unique challenges of Antarctica, including the cold climate, isolation, logistics challenges and environmental regulations are presented, as are other items which may be less apparent to those new to Antarctic plant production facility design projects. Although there have been a number of references that provide an excellent perspective on several of the aforementioned challenges [3-6], this paper strives to provide the first broad reference document designed for Antarctic plant production facility developers. Such information is also useful for those exploiting space analogue sites for space hardware and operations advancement.

II. Actual Antarctic Facility Technology Choices

There are currently (at the time of publication) ten plant growth systems, managed by six different countries, operating in Antarctica (Figure 1): The hydroponic facilities at the Australian Davis, Casey, and Mawson stations [7-9], the Chinese Great Wall Station greenhouse and the temporary Zhongshan vegetable growing facility [5, 10, 11], the Japanese Syowa Station growth chamber [12, 13], the New Zealand Scott Base benchtop hydroponic unit [14, 15], South Korea's King Sejong and Jang Bogo stations plant factories [16-18], and the South Pole Food Growth Chamber (SPFGC) at the United States' Amundsen-Scott South Pole Station [6, 19, 20].

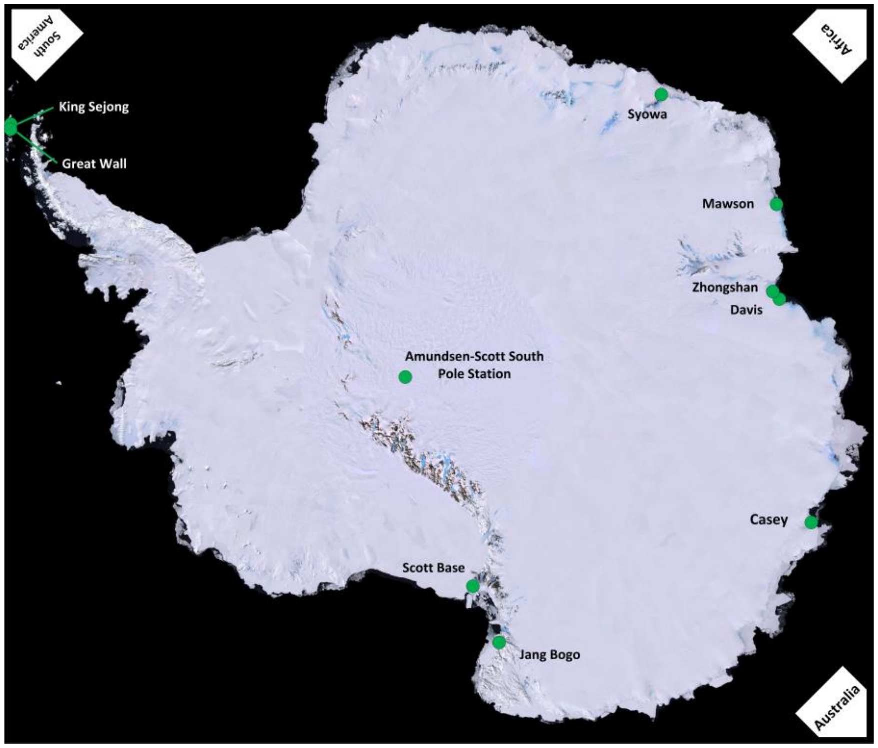

Figure 1. Map depicting operational Antarctic plant production systems. The name of the station at which each facility was installed is indicated (outline Antarctic image credit: Landsat imagery courtesy of NASA Goddard Space Flight Center and U.S. Geological Survey).

The ten presently operating plant production systems have been in use for varying lengths of time and have been summarized in a previous review [1]. The Zhongshan vegetable growing facility was not previously described [1]. This facility was established in early 2014 and is located in a room internal to the Zhongshan Station [11]. It was constructed as an interim facility and will operate until a permanent facility is completed during the upcoming 2016/2017 Austral summer field season [11]. The yet to be built Zhongshan Station facility is planned to follow the same design of the Great Wall Station greenhouse [11]. A summary of the configurations and technologies used in current Antarctic greenhouses is provided in Table 1. This summary information provides a baseline perspective for discussions surrounding Antarctic plant production facility trade-offs and lessons learned.

Table 1. Summary of technology choices for currently operating Antarctic plant growth facilities.

National Program	Station/ Facility	Facility Area (m^2)*	Shipping Container (Y/N)	External Facility (Y/N)	Multilevel System (Y/N)	Lighting Type	CO_2 Enrichment (Y/N) and Target	Nutrient Delivery System
Australia	Casey	27.7	Y	Y	N	HPS, fluorescent	N	NFT, drip-irrigation
	Davis	13.9	Y	Y	Y - up to 2	HPS, fluorescent	N	Mostly NFT
	Mawson	28	N	Y	N	HPS	N	NFT, drip-irrigation
China	Great Wall	36	N	Y	Y	Natural, HPS, LED	Y – 600 ppm (max)	Ebb and flow
	Zhongshan	16	N	N	Y – 2	LED, HPS	N	Ebb and flow, drip-irrigation
Japan	Syowa	~3	N	N	Y - 5	Fluorescent	Y - 1500 ppm (max)	NFT
New Zealand	Scott Base	~0.8†	N	N	N	Fluorescent	N	NFT
Republic of Korea	King Sejong	27.7	Y	Y	Y - 3	Fluorescent, LED	N	Ebb and flow
	Jang Bogo	35	N	N	Y - up to 3	Fluorescent	N	Drip-irrigation, bottom-watering
USA	SPFGC	41.3	N	N	Y	Water jacketed HPS, LED	Y - 1000 ppm	NFT, DFT

*Facility area includes the entire floor area of the plant production facility (cultivation area, subsystem area, walkways, etc.) but does not consider additional cultivation area provided by the incorporation of multilevel growing systems.

†Cultivation area listed as this is a small-scale system located within a main station room.

HPS = high pressure sodium, LED = light emitting diode, NFT = nutrient film technique, DFT = deep flow technique.

A. Facility Type

As is apparent from Table 1, current Antarctic plant production facilities are a mixture of small-scale facilities, like the Japanese Syowa Station plant culture system and the tabletop hydroponics unit at the New Zealand's Scott Base, and larger facilities ranging from 13.9 to 41.4 m^2. It is important to note that the areas listed in Table 1 for the SPFGC and the King Sejong plant factory are corrected versions [6, 18] and should take precedence over those described previously [1]. In particular, the King Sejong plant factory is actually a 2 x 20 ft shipping container facility [18]. Three of the ten facilities operate within shipping containers located external to the main station. The other facilities are either situated directly within the main station buildings or are a separate, purposely built, structure (i.e., not a shipping container), such as the Chinese Great Wall Station greenhouse, the only currently operating Antarctic plant production facility that is an actual greenhouse, and the Mawson hydroponics facility which is located in an old wood/metal clad building [3, 5, 21]. The majority of the current production systems utilize multilevel growing systems. This helps maximize biomass output per unit volume, a valuable commodity in Antarctic stations. The Syowa plant culture system uses a five-level growth system focused primarily on short leafy green vegetables [13].

B. Lighting Technology

The lighting technologies deployed in current Antarctic plant production facilities are varied (Table 1); however, they do generally reflect the range of systems used in most conventional greenhouse and growth chamber applications. The most common has been fluorescent lighting which is used in six of the ten currently operating facilities. High pressure sodium (HPS) has, in the past, also been a popular choice, with the Australia stations using it in all of their hydroponic facilities, along with the SPFGC, Zhongshan Station and the Great Wall Station greenhouse [5, 19]. That said, similar to conventional horticultural lighting systems, light emitting diodes (LEDs) have been replacing the existing technologies used in several facilities and have been baselined in several more recent designs [2, 5, 22, 23].

Historically, the conventional range of electric light technologies available for plant production has spanned fluorescent, incandescent, HPS and metal halide, and has also included less mainstream technologies such as microwave powered sulfur plasma and induction lamps. The relatively recent advances in high efficiency and high output LED technologies have made LEDs the 'go to' technology for controlled environment agriculture (CEA). The unique flexibility of LEDs to deliver a variety of monochromatic lights within a single lighting package allows researchers and facility operators to specifically tailor the spectrum to the photosynthetic and secondary metabolism requirements of their crop(s). Energy is saved not only through the increased efficiency of LEDs relative to some traditional lighting systems, but also through the provision of only the wavelengths that are most efficiently utilized by the plants.

While LEDs are considered 'cool' light sources when compared to incandescent, fluorescent or HID lamps, this is true only of the visible light produced. LEDs, particularly when operated at the high intensities required for growth and development of fruiting plants (e.g., tomato, cucumber, wheat, rice), produce a great deal of heat which must be removed to prevent lamp failure [24]. For most luminaires, sufficient heat reduction can be achieved with a properly designed passive heat sink; however, improved efficiency and longevity are achieved through active cooling using fans or liquid cooling systems. Liquid cooling of LEDs offers the ability to capture waste heat for reuse, either directly in the plant growing space or for heating subsidiary living spaces. Without a massive heat sink or fans, liquid cooled LEDs can also provide a light source with a very low profile, allowing for greatly improved plant production volumetric efficiency. Each layer of a vertical growing space can be custom sized to the crop, with little vertical loss due to lighting systems.

In remote locations such as the Antarctic, Arctic, deserts or even the Moon or Mars, LEDs provide advantages when compared to conventional lighting sources for horticultural use including:

- Low profile to improve volumetric efficiency – more plants per unit volume
- Spectral manipulation to allow custom light recipes for optimal plant production
- Liquid cooling allows for better thermal management and recovery of waste heat for other applications
- Relatively low energy consumption and improved longevity decreases resupply consumables

As evident in Table 3 (section III.A), the low latitudes of Antarctica stations imply a dark season of several months. This, combined with low summer sun angles at such low latitudes, imply that light levels are reasonably low, even in mid-summer. Although some minor growth has been conducted in the austral summer using only natural light, electrical lighting is obviously a requirement to conduct any plant growth during the winter months (when fresh produce is most important due to logistical restrictions).

C. CO_2 Enrichment

As plant growth is determined to a large extent by the rate of CO_2 uptake of the leaves, and since relatively high intensity electrical lighting systems are used, Antarctic plant production facilities can benefit from CO_2 enrichment (particularly true for facilities located on the Antarctic plateau where the altitude implies lower CO_2 partial pressures). Unfortunately, the transportation of CO_2 and the associated tankage and distribution components to Antarctica comes at a cost. A trade-off should be conducted between the amount of CO_2 required and the logistical requirements of bringing CO_2 compared with the expected biomass production increase. The safe handling of CO_2 in closed environments must also be considered, with careful consideration of the location of bottles and distribution equipment, be it within the facility or externally located (in the ambient environment). Storing CO_2 bottles and distribution equipment external to a facility reduces the likelihood of an uncontrolled leak occurring internal the facility and may save precious internal space. Uncontrolled CO_2 leaks can be particularly dangerous if the facility is relatively tight from an atmospheric perspective. Depending on their size, care in such facilities will also need to be taken with regard to crew output CO_2. In both cases, a reliable CO_2 monitoring system is essential. Questions of safety, ease of handling, and nominal Antarctic station logistics chains are factors in the selection of the CO_2 bottle sizes to be used. The Neumayer III greenhouse module project EDEN ISS, due to its closed atmosphere design, has selected CO_2 enrichment and intends to store the bottles externally. Analysis has shown that this is feasible even with temperatures reaching as low as -50°C, both from the perspective of the CO_2 itself and the temperature ratings on the distribution equipment (tank pressure, planned flowrate and other aspects are important considerations). Three of the currently operating Antarctic plant production systems utilize CO_2 enrichment; Japan's Syowa growth chamber, China's Great Wall Station greenhouse and the US SPFGC [5, 6, 13]. Interestingly, rather than directly transporting CO_2, the Japanese Syowa growth chamber uses a CO_2 concentrator to concentrate CO_2 from the ambient atmosphere [13]. The

Australian Sub-Antarctic Macquarie Island Station incorporates a hydroponics unit that includes an on-site CO_2 generator (gas burner type) [9].

For reference, the SPFGC in 2006 injected on average 1.1 kg of CO_2 per day which resulted in an annual shipment requirement of 409 kg of CO_2 to South Pole. When including tankage and related shipment hardware this equated to 818 kg of material (CO_2 supplied from 22.5 kg bottles) [6]. These CO_2 requirement values were primarily driven from the 22.77 m^2 plant growth area, 17 hour photoperiod and a $ppCO_2$ setpoint of 1000 ppm (day) including a measured 610% volume exchanges per day leak rate (CO_2 losses due to air leakage ca. 0.39 CO_2 kg/day) [6]. The Great Wall Station greenhouse when considering a 30 m^2 production area and a $ppCO_2$ setpoint of 300-600 ppm (unknown leakage rate) considered a 600 g CO_2 requirement per day of which 70% is considered to be supplied through natural ventilation and 30% from transported CO_2, amounting to a transport requirement of 0.2 kg/day useable CO_2 [5].

D. Nutrient Delivery System / Irrigation

A range of nutrient delivery systems are being utilized in current Antarctic plant production systems (Table 3). The nutrient film technique (NFT) has been the most popular with six out of ten facilities employing it, at least in some form. A number of the more recent, but non-functional Antarctic greenhouse systems also chose NFT; in particular the Módulo Hidropónico Experimental at the Chilean O'Higgins Station [25], the Indian Maitri Greenhouse [26], the US McMurdo Station greenhouse [27], and the Plant-based Unit for Life Support in Antarctica (PULSA) of the Italian Mario Zucchelli Station [28]. Minimizing waste, both from the hydroponic solution and any utilized growth substrate, is an important driver in the selection of the nutrient delivery system, especially in Antarctica where dealing with waste, e.g., rockwool slabs, can be a costly logistics challenge. For two equivalently performing systems, a developer would obviously prefer the one that utilizes no growth substrate. All present Antarctic plant production systems attempt to recirculate their nutrient solutions to the greatest extent possible. A number of stations claim to have not 'yet' produced waste nutrient solution, but it is highly likely that every facility will require disposal at some point, in particular if a facility is to be shut down during a certain period of the year or if an infestation is observed. With this in mind, Table 2 presents how each of the presently operating hydroponic facilities manages their nutrient solution waste, as well as the type of wastewater processor available at the specific station. Also illustrated in the table is whether or not the station is located on ice-free ground, which is not only relevant to water processing but also to construction and compliance with the Madrid Protocol (section III.B).

Table 2. Summary of waste nutrient solution processing or disposal for currently operating Antarctic plant production systems.

Station	Station on Ice-free Ground (Y/N)	Station Wastewater Processor Type	Nutrient Solution Waste Processing
Syowa	Y	Biological (activated sludge treatment coupled with a membrane separation process) before discharge into the sea [29].	Processed in station sewage treatment plant. Waste solutions not often produced [13].
Great Wall	Y	Chemical treatment prior to discharge into tidal basin [30].	Processed in station sewage treatment plant [5].
Zhongshan	Y	Biological (membrane bioreactor) [31, 32].	Waste solution only rarely produced. When produced, it is processed in the station sewage treatment plant or evaporated directly within the facility and the salts shipped out of Antarctica [11].
Amundsen-Scott South Pole	N	No treatment: Water discharged into deep ice pit [31].	No treatment: Disposed with other station wastewater (all untreated) in deep ice pits [6].
King Sejong	Y	Biological (internal circulation sequence batch reactor). Treated water is discharged into pebble zone in tidal area. The sludge is shipped out of Antarctica [18, 29].	Normally no waste solution produced. Only in off-nominal cases (high microbial load) is waste processed in station sewage treatment plant [18].
Jang Bogo	Y	Biological (internal circulation sequence batch reactor) followed by a membrane bioreactor and ozone oxidizer before discharge into the sea [29, 33].	No waste solution yet produced. If produced, all wastewater will be shipped out of Antarctica [18].
Davis	Y	Mechanical and biological (membrane bioreactor) before discharge of the effluent through an outfall into the sea [9, 31].	Processed in station sewage treatment plant [9].
Casey	Y	Biological (rotating biological contactor), mechanical and UV [31].	Processed in station sewage treatment plant [9].
Mawson	Y	Biological (rotating biological contactor) [31].	Processed in station sewage treatment plant [9].
Scott Base	Y	Biological (contact aeration) and UV [31].	Processed in station sewage treatment plant [34].

The amount of nutrient solution wastewater, even if facilities are not able to recirculate for several months at a time, are actually typically a very small contribution to overall station wastewater streams. Indeed, even the relatively high nutrient content that can be expected in the nutrient solution wastewater should not be of considerable concern when comparing this to the volumes of nutrients expected in, for example, station crewmember urine and within other nominal waste streams. For example, in the analysis being conducted for the Neumayer III EDEN ISS greenhouse module, a worst case scenario of nutrient solution recirculation for a duration of six weeks is considered, in which 500 L of nutrient solution would need to be disposed of. If a half strength Hoagland nutrient solution is considered as the baseline hydroponic solution, then an estimate of approximately 550 g of salts would be included in this solution. This agrees well with the Australian facilities which have been designed to recirculate approximately 150 L of nutrient solution for a period of 2-4 weeks before replacing it (Australian IEE). That said, the nutrient solution wastewater is only a part of the overall wastewater stream that can be expected from a plant production system. A likely more significant contribution is from cleaning water, which for the Neumayer III greenhouse module is estimated at an upper bound of 200 L per week, with another conservative estimate of 5 L of water for germination. The cleaning water can be assumed to include some soap and minor amounts of cleaning chemicals. Antarctic greenhouse developers need to be able to estimate overall wastewater volumes and composition to ensure that such streams can be processed by the specific wastewater processor (if applicable) at the station where the facility will be located.

Although there are numerous nutrient solution recipes defined in the literature, the majority are defined as "modified Hoagland solutions" and all contain the same basic components with only slight to moderate variations in salt ratios and minor constituents that are defined for different species/cultivars or plant growth stages. In general, plants will utilize the nutrients they require, leaving those that are in excess. Advanced recipes are developed to reduce excess nutrients as the plants develop. In typical nutrient solutions, electrical conductivity values (EC) range between 0.8 and 2.4 mS with typical 200 ppm N recipes containing a total salt content of approximately 2 g L^{-1}. In addition to the expected volumes of nutrient solution requiring disposal, the approximate ion concentrations must also be considered when evaluating the added burden on an Antarctic station's wastewater treatment system. That said, it is important to compare such waste streams with the streams already coming from nominal station operations. For example, human urine is made up of ca. 95% water, with urea, chloride, sodium, potassium, creatinine and other dissolved ions, inorganic and organic compounds. Urine is approximately 10 times more concentrated than nutrient solution, with EC values averaging 21.5 mS [35]. Considering the typical crew of nine at Neumayer Station III and an average output of 1.5 L/day per person, total human urine production for a three week period can exceed 280 L, with a salt content in excess of 3.8 kg.

As a waste product, spent nutrient solution can be, and is for the most part, easily processed using existing waste treatment systems at Antarctic stations. Disinfection procedures for nutrient systems prior to plant production often use chemical treatments such as sodium hypochlorite or commercial treatments like Virkon (Dupont); however, these chemicals can leave residues and are not [necessarily] compatible with small-scale waste treatment systems, particularly those based on biological processes. Hydrogen peroxide is also a common disinfectant however it must be supplied/shipped in concentrated form. The use of ozone (O_3) for disinfection of hydroponic systems has been gaining popularity as it is produced on-site and is an effective, broad spectrum disinfectant that can also degrade many chemical contaminants that may pose a phytotoxic risk to the crop. Aqueous ozone also leaves no residue that can harm downstream waste treatment operations.

The final consideration of a nutrient system is the choice of substrate. As all Antarctic plant production facilities use soilless hydroponic systems (Table 1) due to the Conservation of Fauna and Flora stipulation of the Madrid Protocol, the choice of media is limited to non-organic products. The growing substrate is required to help physically support the shoot mass and hold moisture while allowing for adequate oxygenation of the root zone.

III. Main Antarctic Plant Production Design Drivers: Lessons Learned from Past Systems

A. Climate

Although often perceived as uniformly cold and desolate, there is significant variation in the climate between Antarctic locations, with more temperate climes found at more northern latitudes and near coastal areas, particularly along the Antarctic Peninsula. More severe temperature and weather localities can exist at inland locations and on the Antarctic plateau. Table 3 presents environmental parameters for three representative Antarctic locations to demonstrate the general variation across the Antarctic continent. It should be noted that weather at any given station is very site specific with weather also being affected by topographical influences and other site specific factors.

Table 3. Summary of a comparison between the environmental parameters of three representative Antarctic locations.

Location		King George Island / Antarctic Peninsula	Ring of Antarctic Continent	South Pole
Example Station Used		King Sejong 62°13.40'S 58°47.35'W Elevation: 10 m	Neumayer III 70°38.00'S 8°15.80'W Elevation: 40 m	Amundsen-Scott 89°59.85'S 139°16.37'E Elevation: 2830 m
Environmental Parameters				
Temperature	Austral summer (max)	+13.2°C [36]	+4.5°C [37]	-12.3°C [38]
	Austral winter (min)	-25.6°C [36]	-50°C [37]	-82.8°C [38]
	Annual average	-1.7°C [36]	-16.1°C [37]	-49.4°C [38]
Humidity*	Mean	88.9% [39]	70-95% [40]	69.7-81.0% [41]
Pressure	Mean	98.9 kPa [39]	98.7 kPa [42]	68.12 kPa [38]
$ppCO_2$	Mean	~400 ppm [43, 44]	~400 ppm [45]	~400 ppm [46]
Wind speed	Mean	8.0 m/s [39]	9.1 m/s [37]	4.1 m/s [38]
	Max	41.2 m/s [36]†	50 m/s [37]	25.9 m/s [38]
Light level	Austral summer (max)	~1100 W/m^2 [47]	960 W/m^2 [48]	~750 W/m^2 [49]
	Austral winter (min)	0 W/m^2‡	0 W/m^2 [48]	0 W/m^2 [49]
	24 hour sunlight	N/A‡	~Nov 16 to Jan 27 (73 days) [50]	~Sep 23 to Mar 18 (178 days) [51]
	24 hour darkness	N/A‡	~May 18 to July 27 (73 days) [50]	~Mar 20 to Sep 21 (186 days) [51]
Snow accumulation§	Annual total	48.4 cm precipitation (total accumulation higher) [39]. Antarctic Peninsula typically has the highest precipitation in Antarctica [52].	~100 cm [37, 53].	27.5 cm. Polar plateau has lowest precipitation in Antarctica [38, 52].

*Absolute humidity is very low.
†Only considers full-year monitoring period in 2011.
‡Outside Antarctic circle.
§Undisturbed areas. A separation into precipitation, evaporation and drift snow contributions is difficult and has so far not been investigated. Presented values are estimates.

The environmental parameters shown in Table 3 influence the design of Antarctic plant production facilities in a significant way. One major design driver for facilities located externally to main Antarctic station buildings is snow accumulation (e.g., combination of precipitation and drift); however, actual snow accumulation estimates across the continent remain largely unknown [52]. In any case, some general trends and observations can be concluded, such as typically higher snowfall in coastal regions due to proximity to warmer ocean water, higher local air moisture, more cloud condensation nuclei from the salty water and the often sharp ice edge itself compared to the interior of the continent [52]. In Antarctica, blowing and drifting snow is very common due to high wind speeds at most locations. Buildings can block or disrupt the wind flow resulting in snow being deposited at or near the building; the Neumayer III greenhouse must itself be located approximately 300 m from the main Neumayer III station to account for this drifting effect. This positioning in itself influences the operations of the facility in a major way with respect to the considerable transport of items to and from the main station to the greenhouse. Additionally, the greenhouse module is being built on an elevated platform which allows the snow to pass below the facility to reduce local accumulation and prevent the facility from being buried, as has occurred with Antarctic stations in the past. The elevated platform is adjustable and can be raised every few years, which is less work than continuously removing the accumulating snow from around the facility.

B. Antarctic Treaty System

The Antarctic Treaty was developed to ensure that Antarctica will be used for peaceful purposes, that Antarctica will be a location where the freedom of scientific investigation and collaboration therein can continue, and that such scientific data shall be exchanged and made freely available. The Treaty itself resulted in a number of other agreements coming into force. Although other agreements exist, the Protocol on Environmental Protection (Madrid Protocol), Convention for the Conservation of Antarctic Seals, and Convention on the Conservation of Antarctic Marine Living Resources are the three primary foundational agreements. The Antarctic Treaty, with its corresponding agreements, form the Antarctic Treaty System. The Treaty System, as it should, significantly influences the design of Antarctic plant production facilities. This is particularly true when considering design implications that could affect the introduction of non-native species, waste handling, material choices and overall project approval and permits. Such requirements stem specifically from the Protocol on Environmental Protection. A top-level summary of several of these requirements and the specific Annex from which they originated is displayed in Figure 2.

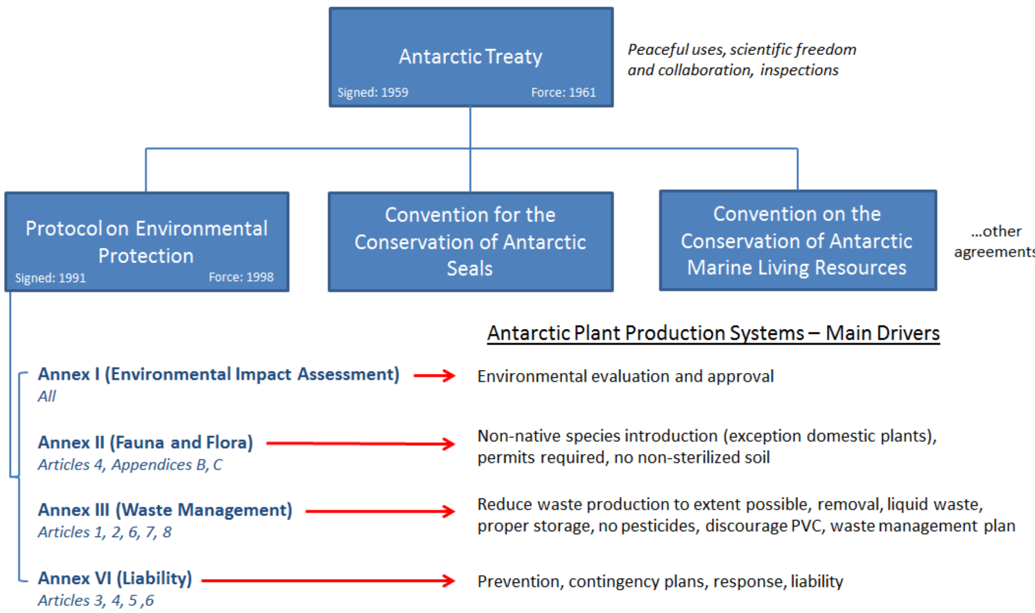

Figure 2. Antarctic Treaty System and its specific influences on Antarctic plant production systems.

Although in principle all Annexes influence Antarctic activities, Annexes I, II, III and VI of the Protocol on Environment Protection have elements that must be specifically considered by plant production facility designers. Annex I (Environmental Impact Assessment) mandates facility designers to assess their possible impact on the Antarctic environment. Impact levels are bound by categories such as ‘less than minor or transitory impact’ or ‘more than minor or transitory impact’. In both instances an evaluation document must be drafted. In the case of plant production facility projects that have ‘less than minor or transitory impact’ an Initial Environmental Evaluation (IEE) must be drafted, whereas projects with ‘more than minor or transitory impact’ must submit a Comprehensive Environmental Evaluation (CEE). In both cases, the report must describe the proposed activities, its purpose, location, duration and intensity. Also of importance is the consideration of alternatives to the proposed activity and the inclusion of a review of those impacts as well. A CEE, as the name suggests, entails a significantly higher level of detail than an IEE and must detail a suite of factors such as the methods and data used to forecast the impacts of the proposed activity, possible secondary or indirect impacts of the proposed activity, monitoring programs or measures that could be taken to mitigate or minimize the impacts or detect unforeseen impacts, etc. Approval of the submitted IEE or CEE must be obtained before any activities can proceed.

As illustrated in Figure 2, Annex II (Conservation of Fauna and Flora) of the Madrid Protocol focuses heavily on the possible introduction of non-native species to Antarctica. Specifically, Annex II states: ‘No species of animal or plant not native to the Antarctic Treaty Area shall be introduced onto land or ice shelves, or into water in the Antarctic Treaty Area except in accordance with a permit’. This Annex is of obvious and direct relevance to Antarctic plant production systems. As the types of crops that most Antarctic plant production systems wish to grow are not native to Antarctica, the opportunity to transport them to Antarctica would otherwise be restricted except for the fact that Appendix B of the Annex details exceptions regarding the import of animals and plants. In particular, that domestic plants (i.e., food/crop species) can be imported when the appropriate permits are obtained. Another main element, primarily stemming from the prevention of the introduction of microorganisms into the Antarctic ecosystem, is that the importation of non-sterile soil should be avoided to the maximum extent possible. This itself highly suggests that plant production facilities, as they have in recent decades, should utilize hydroponic systems.

Annex III (Waste Disposal and Waste Management) imposes several constraints that may impact plant production system designs, and which are primarily focused on preventing facility waste from impacting the local environment. Specifically, the constraints focus on reducing the amount of waste produced and on appropriate removal or disposal of waste products generated. Facilities must plan to remove a great portion of waste, with specific focus on things such as batteries, toxic or harmful compounds (e.g., nutrient salts or concentrated acids and bases used to make up hydroponic solutions) and several plastics that make up plant growth systems. Proper storage to prevent inadvertent dispersal is a necessity. Although there should be a preference to continually recirculate the hydroponic nutrient solution, some waste nutrient solution and general wastewater (e.g., cleaning) will be generated within an Antarctic greenhouse. Annex III provides guidance on how such wastes could be handled or disposed. The Annex also discourages or prevents the use of a number of materials that may otherwise be common place in traditional plant production system; particularly, pesticides (except under very specific conditions), polyvinyl chloride and a number of specific packaging materials (e.g., polystyrene beads, chips). Finally, the Annex requires that facility operators develop an overall waste management plan.

Annex VI (Liability Arising from Environmental Emergencies) focuses on the prevention of incidents that have the potential to negatively influence the Antarctic environment and stipulates that parties planning activities in Antarctica must develop contingency plans and how they will respond to such incidents. For proposed plant production systems these plans should detail procedures to respond to such things as the discovery of non-native species, or procedures on how the operators would react to waste generated from the facility should it be accidentally released to the external environment. The Annex also describes how facility operators can be liable for incidents that occur.

Often, countries have transformed the text of the Antarctic Treaty into laws in their own respective countries that their national operators and researchers must abide by when conducting activities at the country's station. Australia and France have also compiled guidelines specific to minimizing the risks of non-native species and disease associated with hydroponic facilities in Antarctica that they submitted as a working paper to the XXXV Antarctic Treaty Consultative Meeting in 2012 [4]. It was previously discussed that an Antarctic plant production facility, just like any other project proposed within the Antarctic Treaty Area, would have to apply for a permit, typically to the national environmental agency within the country that the project is originating. The following items are an extract of a typical project permit application and those of specific relevance to Antarctic plant production projects [54]:

- Antarctic location
- Project team and polar experience
- Duration of project, dates of arrival and departure of the field team, mode of travel (team, cargo)
- List of other projects dealing with similar subjects/approaches (i.e., past Antarctic greenhouse projects)
- Description of project requirements to build/install on-site infrastructure, as well as estimates of the on-site logistics requirements (aircraft, tracked vehicles, generators, etc.) and estimated hours of operation
- Description of how solid and liquid waste will be managed
- List of chemicals, cleaning supplies or other substances that may be emitted into the Antarctic environment (e.g., nutrient salts, acids, bases, etc.) and how emissions/discharges will be reduced to the extent possible
- Description of measures taken should an accident/emergency occur or in case of the accidental emission of these substances into the environment (e.g., seed species and quantities)
- Whether the project will introduce non-native species into the Antarctic and a description of said species
- Whether any of the activities affect Antarctic specially protected or specially managed areas

Based on this information, the respective national environmental agency will determine if the project can be classified as having 'less than minor or transitory impact' and thus complete an IEE, or must complete the more detailed CEE. For reference sake, several other Antarctic plant production facilities have in the past been classified as having 'less than minor or transitory impact' and have thus completed IEEs [3, 5].

C. Introduction of Non-Native Species

Due to the inhospitable climate of Antarctica the risk of introducing non-native species from plant production units is often considered of low probability in early designs. This is a misconception due to the fact that greenhouses themselves provide an environment where certain non-native species can thrive and, depending on the location of the greenhouse itself, have the potential to establish themselves in the local environment. A distinction between plant production facility locations can then be made with respect to whether it is located on the ice sheet or ice shelf, or if it is located in one of the natural snow and ice-free areas often termed Antarctic oases. These ice free areas provide much more favorable conditions for the establishment of introduced species. Facilities on permanent snow/ice have a reduced risk of non-native species establishing themselves in the local environs, though this risk is not completely eliminated.

For reference, the location of current Antarctic plant production facilities with respect to ice or ice-free locations is shown in Table 2 section II.D. The documented cases of non-native species being observed during the operation of past plant growth facilities are shown in Table 4. It is important to note that these only represent the published occurrences of observed non-native species and that many other incidents have likely occurred.

Table 4. Summary of documented observations of non-native species within Antarctic greenhouses.

National Program	Station Name	Non-Native Species	Dates
Australia	Casey	Springtails, nematodes, mites, saprophytic fungi	1980
	Casey	Flies, mites, springtails, moss, clover	Mid-1980s
	Davis	Onion thrip, springtails	1986-1987
	Davis	Springtails	2014
New Zealand	Scott Base	Springtails	2002
	Scott Base	Springtails	2004
Poland	Arctowski	*Poa annua*	Late 1970s
USA	McMurdo	Springtails	2003, 2004
	Amundsen-Scott South Pole	Mites	2006, 2010

There are numerous vectors by which non-native species have found their way to Antarctica, not always directly due to the plant production facility or its associated logistics chain. For example, in the case of Arctowski Station where *Poa annua* (annual bluegrass) has established a breeding population (the only flowering plant species in the Maritime Antarctic that has been thought to do so due to anthropogenic means), research has demonstrated that although it is highly likely that the diaspores of *Poa annua* were transported to Antarctica within unsterilized soil used within the greenhouse, *Poa annua* has likely been introduced not just once but several times through multiple vectors [55]. *Poa annua* is representative of the direct anthropogenic introduction of an invasive species into Antarctica that has expanded from inhabiting areas near human activities into tundra communities [55]. Springtails (Collembola) and nematodes were observed in 1980 within scoria (volcanic rock) being used as hydroponic growth substrate within the Casey Station hydroponic growth room [3]. Saprophytic fungi were also observed within the hydroponic system, as were mites in harvested peppers [3]. Various non-native species were again observed within the Casey growth room in the mid-1980s when evidence of mites (Acarina), springtails, moss (Funaria), clover (Trifolium), and even flies (Diptera) were observed [3]. Similar observations were made around the same time at the Australian Davis Station where onion thrip (*Thrips tabaci*) and springtails (*Lepidocrytus pallidus*) were collected from the Davis hydroponics garden [3]. The USA McMurdo greenhouse and currently operating SPFGC have both suffered infestations, with more substantial occurrences occurring at McMurdo in 2003 and 2004 with springtails, and at South Pole in 2006 and 2010 with mites [14]. In certain instances station operators chose to close facilities permanently due to infestations. For example, New Zealand closed the Scott Base hydroponics system in 2005 due, in part, to multiples instances of springtail infestations [15, 56]. Interestingly, the likely source of the Scott Base springtails is thought to be due to the transfer of plants and cuttings into the Scott Base unit from the McMurdo greenhouse [15, 57]. As seen, infestations are still occurring ‘today’ with the described 2010 infestation in the SPFGC and springtails being observed within the former Davis hydroponics facility in 2014 [9, 14].

Potential contaminants of Antarctic hydroponic systems have been described to include sciarid flies (which feed on bacteria, fungi and algal growth), *Thrips imaginis* and *Thrips tabaci* (these being highly mobile on clothing), white flies (Aleyrodidae), some Lepidoptera as well as other mites and springtails (*Proisotoma minuta, Folsomia candida, Lepidocyrtus spp.*, *Onychiurus spp.*) [14]. The provisions of the Antarctic Treaty and the fact that numerous countries have had non-native species issues has resulted in countries enacting specific enhanced measures against non-native species introductions. For example, Poland introduced new, more restrictive phytosanitary regulations related to the access to Arctowski Station in 2013 [55]. A list of a number of key lessons learned or operational strategy suggestions from several of the national operators related to hydroponics include [5, 14, 15, 25]:

- Shutting down the facility during the Austral summer.
- During facility shut down (e.g., during the annual shutdown) the facility should be completely sterilized (full cleaning and sterilization should occur at least once per year).
- Ensure that staff understand their roles in mitigating risks (includes training and a hydroponics manual).
- Regular inspections for disease, algae growth and insects should be conducted (e.g., sticky traps for insects, water samples viewed under microscope to check for algae).
- Any non-native species sightings should be reported immediately to the responsible individual and expert advice sought as quickly as possible (a network of experts should be identified ahead of time).
- If diseases are detected, the entire facility should be shut down and the plants (and all organic materials) removed and incinerated, autoclaved or disposed/removed from Antarctica safely.
- Facility access should be constrained and should generally be reserved for operators and accompanied visitors who have a special interest in the greenhouse.

- A log of facility access/visits should be maintained.
- Individuals entering the facility should have clean hands (preferably disinfected with a detergent) and wear clean clothing and footwear.
- The handling of fresh produce prior to entering the facility should be avoided.
- Only strictly controlled and quarantined seeds and materials should be imported. Cuttings or seeds from imported fresh produce should not be utilized.
- A record of all plants and plant-associated organisms entering or departing the facility should be kept.
- All organic materials (e.g., seeds, trays of seedlings, harvested vegetables etc.) when being transferred to or from the facility should be contained within a closed non-breakable container.
- During storage or handling, seeds should be stored in a spill proof container.

In relation to the suggestion of operating the facility only during the Austral winter, this implies for some facilities, in particular those that may be located in larger (population) station areas or those that are less separated from the living quarters, that these facilities should be shut down during the busy Austral summer. Explicitly, the plant growth system should be shut down and thoroughly cleaned before the arrival of the summer field team and only reactivated following their departure (as conducted with the Scott Base benchtop hydroponic system [15]). Besides minimizing the likelihood of the facility being exposed to the various non-native species vectors presented by the greater number of on-site personal and due to equipment transfer, the summer also typically provides the most conducive environmental conditions for non-native species establishment outside the facility.

Although Antarctic hydroponic systems have an inherent risk related to the introduction of non-native species, the use of the aforementioned operational strategies can reduce this risk. It has been suggested that in-situ food production can actually reduce the risks of non-native species introduction [5]. These assertions are not without basis considering that Antarctic station food is sourced from over 750 worldwide locations (a varying level of quality control is certain) [58]. In addition to soils, invertebrates and microbial plant pathogens having been found on food shipments, there have also been more dramatic examples, such as the discovery of a frog within shipped stores of fresh salad [58, 59].

D. Crew Access

Although restricting personnel access to Antarctic facilities is beneficial from a non-native species perspective, one of the primary benefits of plant production in Antarctica is the positive psychological impact on the crew. This not only includes the fact that the crew can eat the produce (nutritional benefits) but also the visual and olfactory benefit that exposure to the growing crops provides. Some crew will also benefit from active participation in crop production itself. This combined horticultural therapy effect can have real and profound influence on crew morale [60]. Different Antarctic facilities have taken different approaches from this perspective.

Figure 3. The World Park Base main common room (Greenpeace Antarctica Expedition 1991/92) showing the station hydroponics unit to the right side of the room (Image credit: © Greenpeace / Timothy A. Baker).

Early Antarctic plant production facilities did not include any access restrictions, and often times, only one door separated the facility from the outside surroundings. As described in previous work, about half of the past and present Antarctic plant production facilities have been setup within the main station or a main station room such that expeditioners do not have to go outside to access the facility, while half are external facilities in which a crewmember would typically have to don their cold weather gear to reach them. Again, both approaches have their merit with respect to non-native species and psychological benefit [1]. A plant growth facility located within a main station improves accessibility and thus potential for psychological benefit across the entire crew. Two of the more notable examples of plant growth systems directly within the crew living quarters are World Park Base and the current benchtop growth system at Scott Base [15, 61]. The World Park Base hydroponic system (Figure 3) was one of the best examples of facilitating crew access; the hydroponics unit prominently located within the main common room.

The SPFGC, located within the Amundsen Scott South Pole Station, takes a room within a room approach in which an isolated growth room, with glass walls, is situated within a common room that can be accessed by all the crewmembers. This room, as shown in Figure 4, provides a place for expeditioners to relax on comfortable furniture, but also access the internet or a telephone while still seeing the plants and the brightly lit environment of the plant production chamber [6].

Figure 4. The South Pole Food Growth Chamber in a 2006 composite photo showing the anteroom adjacent to the plant production chamber with separating windows/transparent doors (Image credit: Lane Patterson, National Science Foundation).

In general, Antarctic plant growth system developers have been moving towards more contained plant growth systems, with greater access control/restrictions. For example, the proposed, but later cancelled Halley VI hydroponics unit was to stand directly in the central module of the research station and thus, like in the World Park Base case, would be a prominent visual element of the station. But unlike World Park Base, the hydroponics unit was to be contained within a closed-transparent structure, and thus better protected from crew activities [62, 63]. The design of the EDEN ISS greenhouse module which will be a completely separate module from the Neumayer Station III includes some of the most comprehensive protocols with respect to the prevention of non-native species introductions (i.e., access, hygiene protocols, etc.); however, a large transparent door has been baselined to be included between the service section and the primary plant growth chamber to facilitate partial crew access. Providing such 'access' is a high priority but must be balanced by non-native species concerns. Table 5 outlines the pros and cons of the two extreme cases of having a plant growth facility located in the main building of an Antarctic station (with 'full' crew access) versus a completely separate system with restricted access.

Table 5. Summary of factors to consider when choosing between deployment extremes of a plant growth facility (interior with open access vs. exterior with closed/restricted access).

Factor	Fully Open System Located in Main Station Room	Closed System Located External to the Station and with Limited Access
Psychological benefit	Very high as access to plants simplified for all expeditioners. May prove easier for other crewmembers to take plant tending roles and thus interact directly with the plants.	May be limited depending on specific location and measures taken to facilitate ease of access and comfort. May provide a better place for crewmembers to 'escape' depending on configuration. Higher yields (see below), may provide better food consumption related psychological benefit.

Introduction of non-native species	More difficult to control due to greater human traffic, movement in and out of the general station, difficult to keep clean. Advantage is that more access could imply more people taking responsibility for cleaning and enhance monitoring.	Better control of access, movement of materials, ease of closing entire module in the event of an infestation. One negative aspect is that plant materials, waste nutrient solution and general wastes need to be transported between the facility and the general station (depending on configuration).
Yield	May be reduced due to likely non-optimum plant growth environment (e.g., humidity, day-night temperatures, etc.). May or may not catch crop issues faster due to more people viewing crops.	Easier to provide optimum growth environment and cleanliness.
Cost	Cost reduced as system likely simply operating within the general station environmental control system.	Very system dependent but may be of higher cost due to some specialized hardware or configurations being required to ensure that crew provided 'access' (e.g., transparent doors).
Setup	Systems integrated into the main station room, if already considered during the design of the station, require less work to setup than external facilities. However, plant growth facilities incorporated into an already existing station room may cause additional work effort, depending on location of interfaces (water, electricity).	External systems can, depending on the transportation requirements, already be integrated before shipping to Antarctica (in particular for shipping container based systems). This reduces the amount of work to be done during the setup in Antarctica. However, connecting an external facility to the power grid of the station and supplying the plant growth system with water are much more difficult compared to systems located inside the main station.
On-site operations	Plant growth systems inside the main station are easier to operate and maintain by the crew. The crew does not need to don cold weather gear to go to the plant growth facility. The direct access to laboratories and workshops inside the main station are also beneficial. No special means are required to transport plant material from and to the plant growth facility.	An external plant growth facility typically requires the crew to don cold weather gear to reach the facility. The accessibility to an external facility may also depend on weather conditions. Depending on the distance between the greenhouse and the main station, the plant growth facility requires additional tools which would otherwise be easily accessible from the station workshop and laboratories. Dedicated transportation equipment to transport plant material and research samples may be required to operate an external facility.

A hybrid solution based upon the considerations above would include a small plant growth system (e.g., like the Scott Base benchtop unit) in a reasonably accessible area within the main station, complemented by a larger production scale plant growth system in a more controlled area. The small system would address the psychological benefits, while the larger system would act as the food production unit.

Another important factor in the extent of crew access is the level of system automation. Finding the right balance between crewmembers enjoying their roles within the facility while not having them overly burdened is critical for system success. Implementation of specific subsystem automation is an important aspect to consider and is highly dependent on the plant growth facility size, number of overwintering crew, and their specific responsibilities within the overall base operations. For reference, the SPFGC required approximately 3.3 hours per day of labour (considering one person) to operate and maintain [6].

Crew change-outs have also been described as a challenge by plant production facility operators [64]. A great deal of the operational knowledge can be lost as crews are changed unless there is time allotted for hands-on training during crew overlaps; a situation that is becoming increasingly difficult under the constraints of the Madrid Protocol. As previously discussed, the Madrid Protocol and the associated hydroponic guidelines suggested by national operators, suggest plant growth facilities be operated only during the overwinter period (plant growth systems activated after the last flight has departure after the summer field campaign). In this instance, detailed operational training cannot occur, nor can problems be flagged before the operational expertise is lost and shipment of spares can be arranged [64]. For these reasons, numerous countries now conduct organized hydroponic facility training programs for their overwintering staff before they depart for Antarctica [8, 18]. The Australian Antarctic Division uses readily available commercial hardware in their systems, which simplifies pre-Antarctic training (and spare parts). Further, training courses offered to expeditioners prior to departure are run by a commercial hydroponics operator [65].

E. Limited Accessibility: Logistics Chain and Testing

One of the unique aspects of developing plant production facilities for Antarctica is the remoteness of the location(s). Antarctic stations are not easily accessible and for much of the year their crews remain isolated. Antarctic aircraft operations, which are themselves very site dependent, are limited to a maximum five-month window; ship access is even more restrictive. The ease of access to Antarctic sites varies considerably, being highly dependant on location. The stations located on the Antarctic Peninsula or its numerous islands are often considered the most easily accessible, while inland stations, such as Amundsen-Scott South Pole and Vostok, represent the most challenging stations to reach from a logistics perspective. Due to this variation in accessibility, the logistics chain of the German, Neumayer Station III is taken as a reference case. Because of its coastal proximity on the Ekström Ice Shelf at Atka Bay, large cargo can be transported to the general station vicinity by the Polarstern research vessel. The typical over ice distance that the Pistenbullys (tracked vehicles) need to drive between the station and where Polarstern typically parks up against the ice shelf is just over 20 km. Facility developers should be aware of all of the various transport phases and how they may impact their particular designs. For example, the EDEN ISS Neumayer Station III greenhouse module will be:

- Transported by truck from Bremen to Bremerhaven, Germany.
- Loaded onto the Polarstern research vessel and transported to Cape Town, South Africa where other equipment and consumables including food will be loaded onto the boat (travel time approximately four to five weeks depending on the science program).
- Travel from Cape Town to Neumayer III vicinity (travel time approximately ten days when not incorporating an in transit science program).
- Loaded onto a sled and pulled over the ice by a Pistenbulley to Neumayer III (travel time approximately two hours).

Cranes are utilized to move the facility to and from the various transport modes and used to place the facility on its elevated platform (Figure 5).

Figure 5. The rough mass limits of the Neumayer Station III logistics chain as an example for Antarctic greenhouse shipment considerations.

Each of the cranes and vehicles has a mass limitation that needs to be considered. To provide reasonable fresh produce output, the Neumayer III greenhouse module was initially designed to be contained within a 40 ft container. Following initial discussions with the station operators, Alfred Wegener Institute (AWI), it was determined that 40 ft containers could not be easily transported to Neumayer III and that 20 ft containers formed the foundation of the station logistics chain. Thus the design was modified to utilize two 20 ft high-cube shipping containers that could be joined on-site, a major design consideration and one that involves increased on-site construction and complexity. It should be noted that designers are often driven to use shipping containers as they directly fit into established logistics chains and more so, many of the Antarctic stations themselves are built from shipping containers (i.e., numerous containers co-located together and often under, or contained within, some external structure, or with the shipping containers sitting by themselves external to a given station).

The environmental parameters of each of the various transport environments also need to be addressed. For example, although the greenhouse is being designed for Antarctica it may still need to be transported by boat through a warm or hot climate. Transport from Germany necessitates that the greenhouse will pass through the equatorial region where very warm temperatures can be expected. Further design requirements concerning transport need to take into consideration the location of the facility on the boat during transport. As an example, on deck stowage means the facility will be exposed to water, high humidity, and salt spray. Further, shipment by boat often requires that the container be stacked under, on top or beside other containers, this in addition to the fact that container shipment, in particular international shipment, requires valid Container Safety Convention (CSC) safety approval, implies that the container not have any protuberances. In particular, air exhausts or inlets, antennae, ladders and any other external components must be removed for shipment and be reinstalled following arrival at the final destination. Ship transport itself can often imply a highly dynamic environment. Furthermore, for stations that require over land transport upon reaching Antarctic, there can be significant vibration and shock loads depending on the conditions. This drives what systems can be left installed for shipment, how things will be packed, and if any sensitive electronics or hardware require transport by any other means.

The limited accessibility of Antarctica also drives an enhanced need for planning test programs and a spare parts strategy. In the past some Antarctic facilities were designed to use a pre-existing station building and were not tested ahead of time. This is less the case now, or at a minimum, the hardware used within a plant production system is common with that used at another station in which it is known to function well. The latter being the case with the Australian hydroponic program, which now has a very organized hydroponic program with common components used to the greatest extent possible between Davis, Mawson, and Casey stations [3]. Pre-deployment testing is more and more critical as system complexity increases, as with present and future Antarctic plant production systems that strive to maximize production per unit volume. As there is no hardware store in Antarctica, repairs and part replacement must be done with what is available on-site. With ever more complex systems, there is less likelihood that a general spare part will be available at the station that could be used to repair the facility. In this case, the more detailed testing that can be conducted prior to shipment to Antarctica the better. A good example of such an approach is associated with the Chinese Antarctic plant production facilities. In 2014 a copy of the same greenhouse that was planned for construction at the Great Wall Station (an equivalent facility is also planned for Zhongshan Station in 2016/2017) was built in Shanghai. In addition to testing the actual systems, the greenhouse is now used for training crewmembers who will be responsible for the operation of the actual facilities in Antarctica [11]. Sufficient spare part inventories should be included in the overall design and deployment plans for each plant production facility based on an analysis of the various failure modes of the facility and best known lifetimes of the given parts. Complicating the pre-deployment testing program is the fact that although the facility is being developed to operate in the cold climate of Antarctica, it is often being developed in a warmer climate. Specifically, the test campaign is likely to be finalized in the months leading up to the Antarctic deployment, which corresponds to, at least in the Northern Hemisphere, the summer season. This results in a significant discrepancy between the environmental conditions during testing and those expected during nominal operations in the Antarctic, which requires, potentially costly, workarounds. Depending on the system size and desired level of confidence the facility environmental control system and other facility subsystems that cannot be otherwise sufficiently tested in the warm weather should be tested in a controlled environment chamber capable of sustaining freezing temperature (e.g., a cold storage facility).

Finally, the limited access to Antarctica, especially with respect to large components often requiring ship transport, necessitates a hard shipment date. If this shipment date is missed, due to schedule delays or significant problems during testing, then a year-long wait would be required until the shipment opportunity comes about again. This is quite analogous to the launch of a space mission and one of many reasons why Antarctica often serves as an analogue testbed for the development of space hardware.

F. Environmental Setpoints

One major design choice of an Antarctic plant production facility is the level of atmospheric closure. Maximizing plant production per unit volume would benefit from increased closure. This is due to the fact that the external humidity levels are extremely low and that higher yields can be achieved with elevated CO_2 levels. An ‘open’ system is a system that exchanges internal air for external air, with the dual purpose to maintain the appropriate temperature (e.g., in the case of Antarctica for cooling) and to bring in fresh air (removing trace contaminants, removing humidity). A closed facility on the other hand limits the amount of exchange with the external environment and conditions the air to a greater extent ‘internally’ through active means. A top-level comparison of open and closed facilities, assuming that the plant production facility is a standalone unit exterior to an Antarctic station, is presented in Table 6.

Table 6. Comparison between an open (full air exchange between the internal and external environment) and an atmospherically closed facility.

Factor	Atmospherically ‘Open’	Atmospherically ‘Closed’
Humidity	No dehumidifier required, but likely requires a humidifier for start-up and off-nominal operations.	More active humidity control required. Requires dehumidifier to remove evaporated and transpired water.
Energy / heating	More energy required (especially in austral winter) as typically bringing in very cold, dry external air and outputting warm humid air.	Can use internally generated heat to maintain internal temperature, thus likely not requiring large heat source. The internally generated heat though likely requires a thermal system to radiate heat even in the cold climate of Antarctica.
CO_2	When enriching above ambient levels more CO_2 required to be transported and stored on-site, as elevated levels imply added CO_2 exhausted externally. When operating at ambient levels, CO_2 replenishment can be achieved but may require higher rates of air exchange with the external environment.	CO_2 only lost due to overall system leakage. Measurement more important. Safety regulations for personnel inside closed facilities have to be met (e.g., safety devices, ventilation). Active CO_2 addition a requirement.
O_2	The exchange of atmosphere between the greenhouse and the environment typically supports the maintenance of normal O_2 concentrations within the	Closed facilities require monitoring of the O_2 partial pressure. Too low oxygen may result in reduced crew performance or possibly lethal

	facility.	accidents. If the O_2 concentration is too high (e.g., due to crop O_2 production), the fire risk within a closed facility can become a concern [66].
Volatile organic compounds / trace contaminants	No additional hardware required; contaminants exhausted externally.	Filtering required.
Introduction of non-native species	Higher risk due to higher exchange of material and possibility for biological material to exit in air stream. Can solve issue through filtering.	Better due to less exchange of material from inside and outside.
Complexity	Less complex. Would be sufficient to only have an input pipe including a fan and heater and an output pipe and possibly a humidifier.	More complex.
Crew	The internal environment of a greenhouse can be affected by a crew. This is particularly true for the humidity, CO_2 and O_2 levels but also the heat produced. Open systems are less sensitive to these effects. That said, the influence has to be taken into account depending on the number of crew inside the greenhouse, the duration of stay, the degree of work done during the stay and the overall facility volume.	Closed systems lack considerable exchange of atmosphere with the environment. Consequently, the effects of crew present in the greenhouse are typically much stronger and should always be taken into account during the sizing of the environmental control system of the facility.

One possible option is distinct climate areas in the plant production facility. In particular, a zone for the plants and a separate zone for the bulk of the system hardware and the primary operator work area so that the more stringent environmental requirements required by the plants can be softened in certain areas. This also helps ensure that many of the electrical components can operate in a less humid environment. At the same time, it permits the tailoring of the 'service section' environment of the facility more towards human comfort than towards enhancing plant yields. Of particular relevance is again the humidity. In the design of the Neumayer III greenhouse module it was suggested that a setpoint level of 50% would be appropriate in the service section, but in fact the Neumayer III station itself maintains a humidity level in the area of only 25-30%. This range was selected to reduce the harshness of the change for the crewmembers that regularly exit and then reenter the station (i.e., the transition from the very dry external environment to a humid internal environment can be hard on the skin of crewmembers). So, the service section humidity of the Neumayer III greenhouse was instead set to 25-30% while the plant compartment was set at the higher setpoint level of approximately 70%.

An early design choice of larger facilities is also whether or not the plant compartment itself will have distinct climate zones. As known, different crops and even different cultivars require different environmental parameters for optimum growth, so higher yields could be obtained with separate environmental zones. Additionally, more than one compartment implies that staggered cleaning and sanitizing operations can be implemented in the facility which ensures a more or less continual crop supply [65]. A decision on separation of zones with respect to atmosphere (temperature, humidity, CO_2 etc.), lighting zone and nutrient delivery system must also be made by weighing the theoretical yield benefits against the greater system complexity.

With 'closed' atmospheric facilities it may be possible, even in the cold Antarctic climate, that active heat rejection will be necessary. Power draws of high intensity production systems with electrical lighting can be considerable and heat may need to be removed (unless other means are found to temporarily store or convert this heat, e.g., heat exchanges used for snow melt/source water production).

G. Cold Temperature Design Issues

There have been several documented examples where the extreme cold of Antarctica has negatively influenced the design of operational plant production facilities. One particular challenge is the fact that facilities need to be designed to maintain a high humidity while avoiding condensation on cold interior walls, or even more likely, on the less insulated doors, air entry points or cold paths in general (e.g., at a typical grow chamber relative humidity of 70% and a night time temperature of 18°C the dew point is approximately 12.5°C and thus the wall temperature must be maintained above this value). In the Casey hydroponic growing room, which operated in the 1980s, the high humidity in the room resulted in water condensing on the insulated walls and subsequently draining down and freezing the door shut [1, 67]. This resulted in the door having to be pried open on numerous occasions [67]. Other more recent Australian plant growth facilities have experienced similar problems, for example the Davis hydroponic facility, which over its long lifetime (2001/2002 to 2014) was damaged by the weather, had developed several cold paths that resulted in added heat loss and significant condensation issues. In fact, expeditioners were typically wiping up 5-10 L of condensation per day [68]. The operators were able to remedy several issues and made a number of useful suggestions that could benefit future designs. The first was to keep equipment and other materials away from the wall to floor joints, where the cold paths were typically the most significant (panel seems/joints where the seals had failed) and where the floor itself will typically be one of the colder locations [64, 68]. Another is the use of a thermal camera to determine the areas of most concern for condensation. Special attention should be paid to the seal around the door, corners, wall to floor joints, locations where electrical cables enter the facility and input/exhaust air vents [64, 68].

To reduce the concern of external doors freezing shut (itself a safety issue), Antarctic plant production facility designers have also chosen to include doors with heated frames or simply including a heating trace around the door boundary [69]. Additionally, operators which have known about icing around door seals (noted to only occur on the hydroponics building, not other station buildings) included the removal of ice buildup to their weekly checklist [70]. Due to the condensation concern, fiberglass insulation is to be avoided, as any humidity that builds up will freeze and result in solid blocks of ice in the walls, thus reducing their insulative properties [64]. The Mario Zucchelli Station PULSA system also experienced challenges in avoiding 100% humidity, at least in certain places of the facility, and that resulted in the need to adjust climate control system settings to avoid such issues but which negatively influenced the crop [71]. Some important design options for reducing condensation issues are the selection of type and amount of insulation over the entire facility (and thus increasing the interior wall temperature and increasing the corresponding dew point), using triangular inserts of foam/insulation in the corners of the facility, controlling and managing the locations of all cold paths and designing them out when possible, limiting the number of exterior wall penetrations (e.g., attempt to combine entries of wiring, pipes, etc.) and increasing the general air circulation levels within the facility.

Another challenge noted in Antarctic growth chambers is the occurrence of large temperature gradients from floor to ceiling due to insufficient air movement. For example, in the previously described 1980s Casey hydroponic growing room the temperature gradient was as high as 15°C before an oscillating fan was introduced, while PULSA experienced a 4°C to 10°C temperature gradient [67, 71]. Also related to the cold external temperature and the aforementioned discussion on facility location is the fact that there have been documented instances where vegetables have frozen while being transferred from an external plant production facility to the kitchen of the main station [67, 71]. Thus, even such basic items as transfer of the harvested plant material to the main station needs to be considered and resolved when operating in the cold Antarctic climate. The cold weather will also influence decisions on whether any items can be stored external to the facility. As the facility will need supplies to operate for approximately one year before resupply, consumables and spares for this period will need to be stored at some location at the station. To maximize the plant production area of the facility, the best solution would be to store these items in boxes or an empty container external to the facility. The rated storage temperature of the equipment to be stored must be compared against the lowest expected external temperature at the given site.

H. Access to Station Infrastructure

A major item that will influence Antarctic plant production facility design on numerous levels is the ability of the project to count on and access main station infrastructure. This could imply access to nominal site services such as power and water, but also things such as access to laboratory hardware such as measuring scales, microscopes, distilled/reverse osmosis water as well as other laboratory items that would be more important if the project had a more scientific focus (e.g., drying oven, incubator, hardware that could be utilized for food safety or quality measurements, ion-selective sensors). In similar light, researchers may have a desire to return biological samples (e.g., harvested plant material, microbial samples) back to home laboratories. The bulk of these samples will require long-term low temperature storage (no warmer than -20°C) and thus require access to a low temperature station freezer or a mobile one brought explicitly for that purpose (or consideration of the use of an on-site freeze dryer and confirmation that the concentration of the analytes/quality parameters of interest are not affected by the freeze drying process etc.). This low temperature must be maintained throughout the return travel and thus air or ship infrastructure must also be made available, should sample return be required. Similarly, what sort of general tools (e.g., construction) can be assumed to be available from the main station or what tools need to be acquired specifically for the purposes of the project should be considered. Also of relevance is if the project can count upon bandwidth from the station's satellite data link or if a standalone communication system is required. In both instances, if any of the plant health monitoring is going to be done by a remote team, a reasonable data stream will be required to transmit collected images. All of these questions should be posed and discussed with station management so that assumptions can be confirmed early in the project. Station location can also influence the choice of satellite data link that the plant production facility data will be transmitted over. Geostationary communication satellites become less useful the more south the Antarctic station is. For a point of reference, the remote control capabilities of the SPFGC were only available for approximately 13 hours per day due to the lack of access to the chosen communications link [6].

I. Cold Porch and Emergency Exit

Cold porches are used in most circumstances in cold climate buildings as they provide a passive means to buffer the cold air that enters the facility as individuals enter or leave a building. External plant production systems also should include a cold porch. Its size is a trade-off between giving people enough space to comfortably enter the facility and remove and store their large cold weather clothing, while at the same time not being so big that useful facility space is unnecessarily taken. Some cold porch sizes used in past Antarctic plant production facilities are mentioned here. O'Higgins Modulo Hidroponico Experimental facility incorporated a cold porch with a floor area of 1.46 x 2.50 m, while the McMurdo greenhouse had one of approximately 1.5 m x 2.75 m [27, 69]. For the EDEN ISS project a cold porch of 1.5 x 2.15 m is considered.

Depending on the size and configuration of the plant production facility, an emergency exit is something that should be considered (i.e., primarily in case of fire). Originally, in the design of the EDEN ISS greenhouse module a small emergency exit 'hatch' was considered on the opposite end of the facility from the main entrance door. Later, this smaller hatch was replaced with a standard door. The drivers for this change was that commonality could be had with the other door while at the same time, a full size door provides significant benefits for facility access during the construction and testing phase, where there will be high traffic into and out of the facility.

IV. Conclusion

Although the cost of designing, deploying and running Antarctic hydroponic facilities presently outweighs their return in terms of food output, the psychological and nutritional benefit that these facilities provide means national Antarctic operators will continue to operate and install additional facilities [13, 17, 65]. The environmental, logistic and international agreements, such as the Madrid Protocol, do impose a number of unique design challenges on Antarctic plant production facilities. The impact of a number of such design drivers can be appropriately controlled and lessened when they are considered from the outset of the facility design process. Significant experience can be gained from reviewing the wide array of Antarctic greenhouse and growth chambers that have been developed, in particular the more recent and current projects that must conform to the more stringent regulations dictated by international treaties. Early top-level design considerations for Antarctic plant production facilities must include analysis of obvious factors such as cold temperature design, controlled environment agriculture technology selection, and whether the facility will be installed external or internally to the Antarctic station. In addition, less obvious considerations must be taken into account, such as a complete understanding of what station infrastructure can be relied upon, the level of atmospheric closure and how specific national Antarctic operator logistics chains can directly impact facility designs. It is the intent and hope of the authors that this document will aid future Antarctic plant production facility designers as well as those employing Antarctica as a space analogue site to advance bioregenerative life support system technologies and operations by highlighting the numerous inherent challenges and design considerations necessary for success in such an extreme environment.

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